جامعة الملك سعود
King Saud University

FLUID MECHANICS

(AME 3810)

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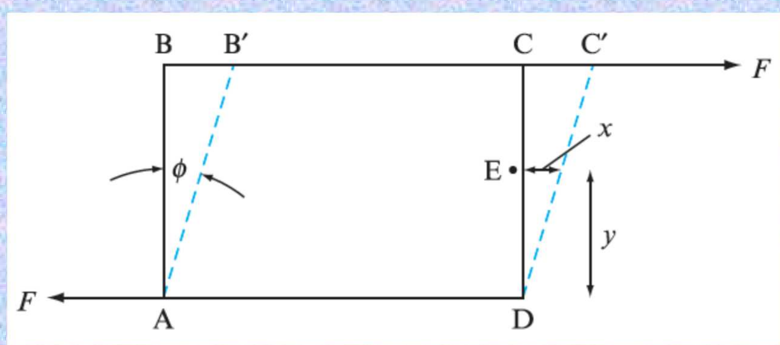
Course Contents

Chapter 2:

Fundamental Concepts in Fluids

Fluid

A fluid is a substance which deforms continuously under the action of shearing forces, however small they may be.



Deformation caused by shearing forces

Basic Equations

1. The conservation of mass
2. Newton's second law of motion
3. The principle of angular momentum
4. The first law of thermodynamics
5. The second law of thermodynamics

+

The ideal gas equation of state

$$P = \rho RT$$

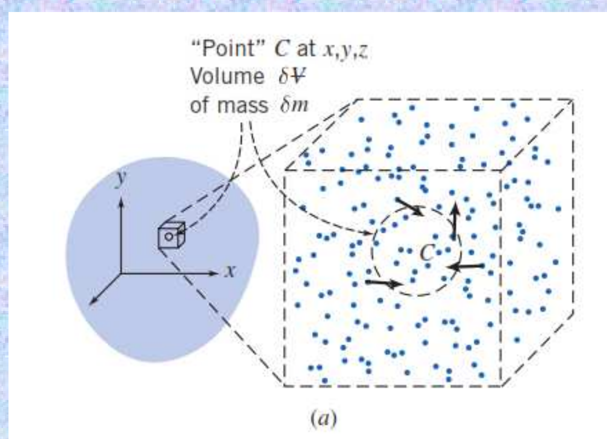
Fluid Properties

Density

Density is defined as mass per unit volume.

$$\rho \equiv \lim_{\delta \forall \to \delta \forall'} \frac{\delta m}{\delta \forall}$$

[kg/m^3]



specific gravity

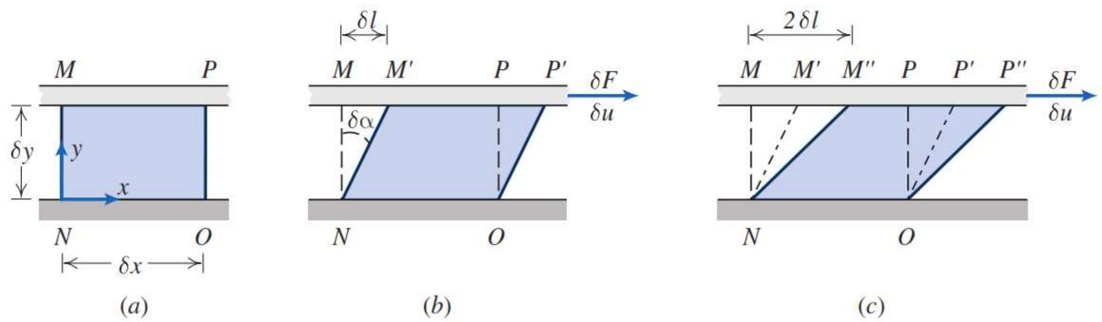
$$SG = \frac{\rho}{\rho_{H_2O}}$$

ρ_{H2O} = 1000 kg/m^3

specific weight

$$\gamma = \frac{mg}{V} \rightarrow \gamma = \rho g \quad \text{N/m}^3$$

Viscosity



(a) Fluid element at time t, (b) deformation of fluid element at time $t + \delta t$, and (c) deformation of fluid element at time $t + 2\delta t$.

The Shear Stress, $\tau_{yx} = \lim_{\delta A_y \to 0} \frac{\delta F_x}{\delta A_y} = \frac{dF_x}{dA_y}$

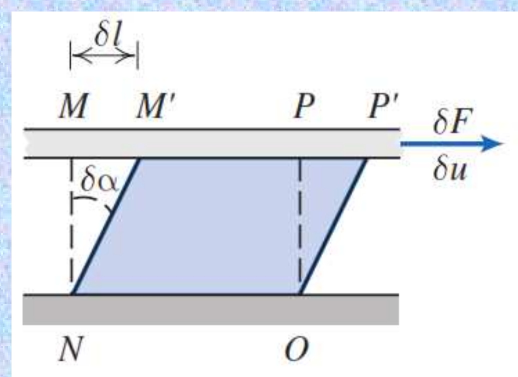
$$\text{deformation rate} = \lim_{\delta t \to 0} \frac{\delta\alpha}{\delta t} = \frac{d\alpha}{dt}$$

$$\delta l = \delta u \, \delta t$$

$$\delta l = \delta y \, \delta \alpha$$

$$\frac{\delta \alpha}{\delta t} = \frac{\delta u}{\delta y}$$

$$\frac{d\alpha}{dt} = \frac{du}{dy}$$



du/dy: (shear rate)

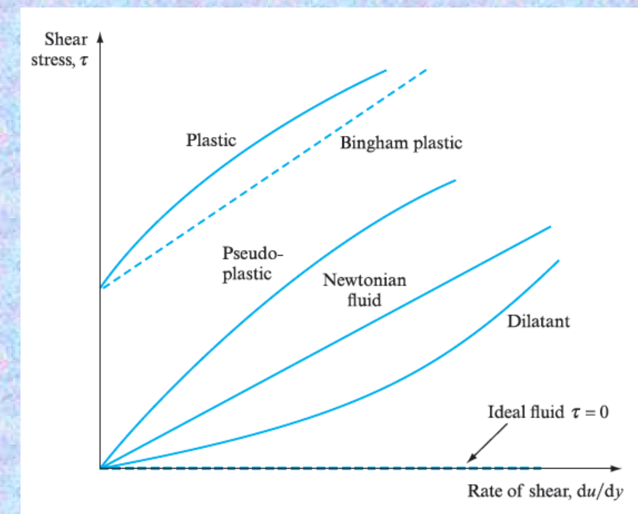
$$\tau_{yx} \propto \frac{du}{dy}$$

$$\tau_{yx} = \mu \frac{du}{dy}$$

Viscosity

Newton's law of viscosity

$$\tau_{yx} = \mu \frac{du}{dy}$$



τ: *shear stress [N/m²]*

μ : The *dynamic viscosity [Pa.s]*

Rate of shear strain = u/*y [1/s]*

Viscosity

The dynamic viscosity (The absolute viscosity)

$$\mu = \tau \Big/ \frac{dv}{dy} = \frac{\text{Force}}{\text{Area}} \Big/ \frac{\text{Velocity}}{\text{Distance}} = \frac{\text{Force} \times \text{Time}}{\text{Area}} \quad \text{or} \quad \frac{\text{Mass}}{\text{Length} \times \text{Time}}.$$

μ : The dynamic viscosity *[Pa.s]*

Poise =0.1 Pa.s

The kinematic viscosity

$$\nu = \mu / \rho.$$

[m^2/s]

stokes (St); [10^4 St = 1 m^2/s]

Newtonian Fluid

Most common fluids such as water, air, and gasoline are Newtonian under normal conditions. If the fluid is Newtonian, then

$$\tau_{yx} = \mu \frac{du}{dy}$$

Non-Newtonian Fluid

Fluids in which shear stress is not directly proportional to deformation rate are non-Newtonian.

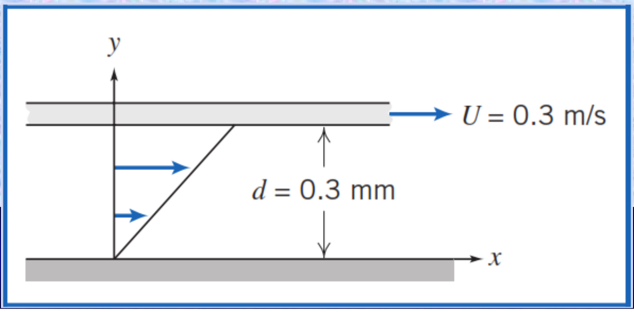
$$\tau_{yx} = k \left(\frac{du}{dy} \right)^n$$

Example: VISCOSITY AND SHEAR STRESS IN NEWTONIAN FLUID

An infinite plate is moved over a second plate on a layer of liquid as shown. For small gap width, d, we assume a linear velocity distribution in the liquid. The liquid viscosity is 0.65 centipoise and its specific gravity is 0.88.

Determine:

(a) The absolute viscosity of the liquid, in $lbf.s/ft^2$.
(b) The kinematic viscosity of the liquid, in m^2/s.
(c) The shear stress on the upper plate, in lbf/ft^2.
(d) The shear stress on the lower plate, in Pa.
(e) The direction of each shear stress calculated in parts (c) and (d).



Given: Linear velocity profile in the liquid between infinite parallel plates as shown.

$$\mu = 0.65 \text{ cp}$$
$$SG = 0.88$$

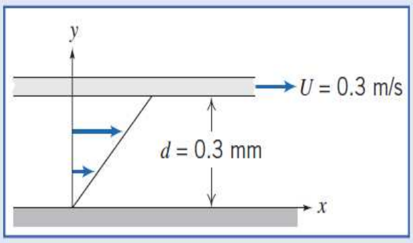
Find: (a) μ in units of $\text{lbf} \cdot \text{s}/\text{ft}^2$.
(b) ν in units of m^2/s.
(c) τ on upper plate in units of lbf/ft^2.
(d) τ on lower plate in units of Pa.
(e) Direction of stresses in parts (c) and (d).

Solution:

Governing equation: $\tau_{yx} = \mu \dfrac{du}{dy}$ Definition: $\nu = \dfrac{\mu}{\rho}$

Assumptions:

1 Linear velocity distribution (given)
2 Steady flow
3 $\mu = \text{constant}$



(a) $\mu = 0.65\ \text{cp} \times \dfrac{\text{poise}}{100\ \text{cp}} \times \dfrac{\text{g}}{\text{cm}\cdot\text{s}\cdot\text{poise}} \times \dfrac{\text{lbm}}{454\ \text{g}} \times \dfrac{\text{slug}}{32.2\ \text{lbm}} \times 30.5\dfrac{\text{cm}}{\text{ft}} \times \dfrac{\text{lbf}\cdot\text{s}^2}{\text{slug}\cdot\text{ft}}$

$$\mu = 1.36 \times 10^{-5}\ \text{lbf}\cdot\text{s}/\text{ft}^2 \longleftarrow \mu$$

(b) $\nu = \dfrac{\mu}{\rho} = \dfrac{\mu}{\text{SG}\,\rho_{H_2O}}$

$$= 1.36 \times 10^{-5}\frac{\text{lbf}\cdot\text{s}}{\text{ft}^2} \times \frac{\text{ft}^3}{(0.88)1.94\ \text{slug}} \times \frac{\text{slug}\cdot\text{ft}}{\text{lbf}\cdot\text{s}^2} \times (0.305)^2\frac{\text{m}^2}{\text{ft}^2}$$

$$\nu = 7.41 \times 10^{-7}\ \text{m}^2/\text{s} \longleftarrow \nu$$

(c) $\tau_{\text{upper}} = \tau_{yx,\text{upper}} = \mu \left.\dfrac{du}{dy}\right)_{y=d}$

Since u varies linearly with y,

$$\frac{du}{dy} = \frac{\Delta u}{\Delta y} = \frac{U-0}{d-0} = \frac{U}{d}$$

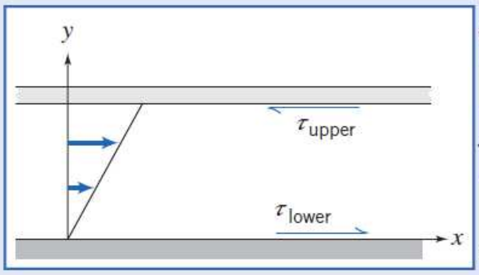
$$= 0.3\frac{\text{m}}{\text{s}} \times \frac{1}{0.3\ \text{mm}} \times 1000\frac{\text{mm}}{\text{m}} = 1000\ \text{s}^{-1}$$

$$\tau_{\text{upper}} = \mu\frac{U}{d} = 1.36 \times 10^{-5}\frac{\text{lbf}\cdot\text{s}}{\text{ft}^2} \times \frac{1000}{\text{s}} = 0.0136\ \text{lbf}/\text{ft}^2 \longleftarrow$$

(d) $\tau_{\text{lower}} = \mu\dfrac{U}{d} = 0.0136\dfrac{\text{lbf}}{\text{ft}^2} \times 4.45\dfrac{\text{N}}{\text{lbf}} \times \dfrac{\text{ft}^2}{(0.305)^2\text{m}^2} \times \dfrac{\text{Pa}\cdot\text{m}^2}{\text{N}}$

$$= 0.651\ \text{Pa} \longleftarrow \tau_{\text{lower}}$$

(e) Directions of shear stresses on upper and lower plates.



{ The upper plate is a negative y surface; so positive τ_{yx} acts in the negative x direction. }

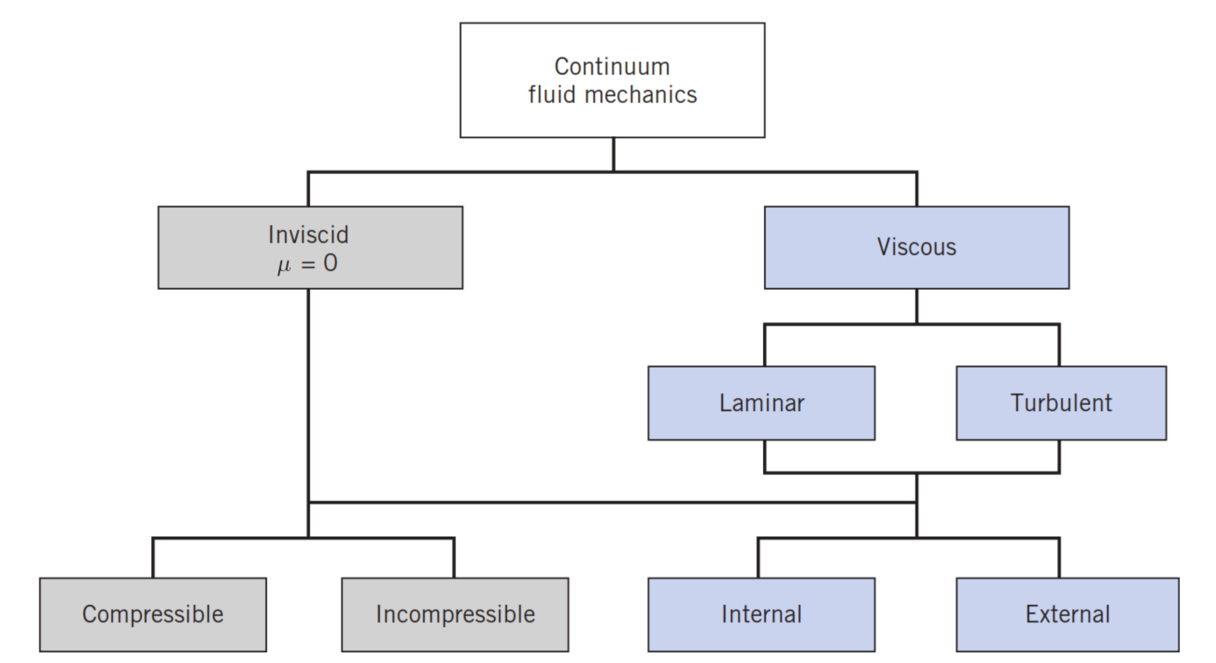
{ The lower plate is a positive y surface; so positive τ_{yx} acts in the positive x direction. } $\longleftarrow$ (e)

Part (c) shows that the shear stress is:

- Constant across the gap for a linear velocity profile.
- Directly proportional to the speed of the upper plate (because of the linearity of Newtonian fluids).
- Inversely proportional to the gap between the plates.

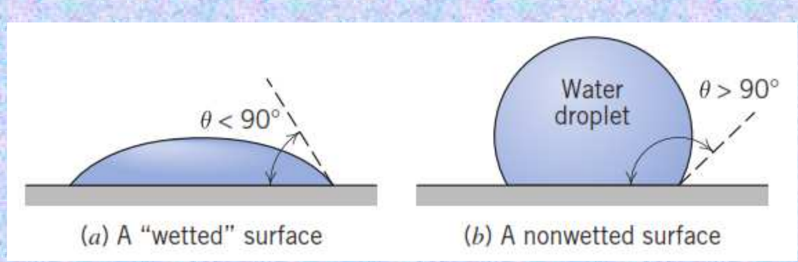
Note that multiplying the shear stress by the plate area in such problems computes the force required to maintain the motion.

Description and Classification of Fluid Motions



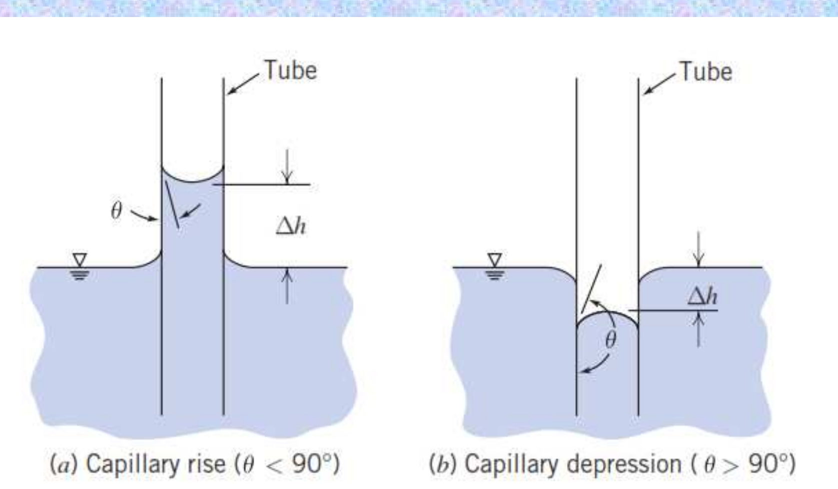
Surface Tension

Whenever a liquid is in contact with other liquids or gases, or in this case a gas/solid surface, an interface develops that acts like a stretched elastic membrane, creating surface tension.

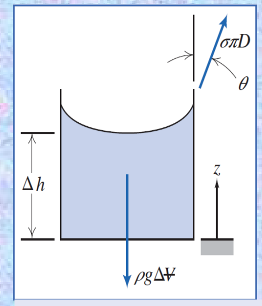


Surface tension effects on water droplets

Surface tension also leads to the phenomena of capillary



Capillary rise and capillary depression inside and outside a circular tube



$$\sum F_z = \sigma \pi D \cos\theta - \rho g \Delta \forall = 0$$

$$\Delta \forall \approx \frac{\pi D^2}{4} \Delta h$$

$$\Delta h = \frac{4\sigma \cos\theta}{\rho g D}$$

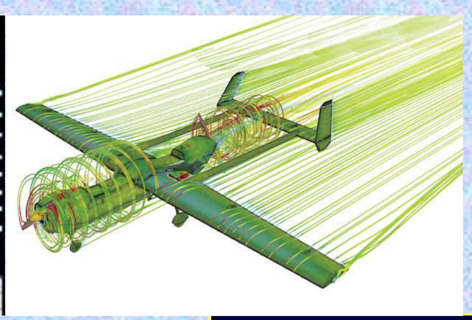
σ : the surface tension (N/m)
θ : contact angle
***D*: tube diameter (m)**

Streamlines and Pathlines

Streamlines **are lines drawn in the flow field so that at a given instant they are tangent to the direction of flow at every point in the flow field.**

Since the streamlines are tangent to the velocity vector at every point in the flow field, there can be no flow across a streamline.

Streamlines are the most commonly used visualization technique.



A *Pathline* is the path or trajectory traced out by a moving fluid particle. To make a pathline visible, we might identify a fluid particle at a given instant, e.g., by the use of dye or smoke, and then take a long exposure photograph of its subsequent motion.

The line traced out by the particle is a pathline. This approach might be used to study, for example, the trajectory of a contaminant leaving a smokestack.